New insights into particle acceleration at relativistic transverse shocks

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Abstract

We have investigated the problem of particle acceleration at relativistic transverse shocks within the framework of the Resonant Cyclotron Absorption (RCA) model. This model (Hoshino et al., 1992; Gallant & Arons, 1994), that has been so far considered the most successful at explaining particle acceleration at the pulsar wind termination shock in plerions, applies to a shock transition occurring in a magnetized relativistic plasma in which electron-positron pairs are the main constituent by number, but most of the energy is carried by a baryonic component.

Previous numerical investigations had shown that resonant absorption of the collective cyclotron waves emitted by the ions at the crossing of the shock lead to efficient acceleration of positrons. These studies were limited, however, to mass-ratios between the ions and the pairs upto a value of 20 (1% of the minimum realistic value).

Since the mass ratio between the species may be crucial, in principle, in determining whether resonant absorption by the pairs is possible, we have extended the previous numerical analyses to larger mass-ratios, confirming the previous results and finding evidence, for the first time, of electron acceleration. Our work also points out that a crucial role in determining whether acceleration is possible is played by the initial degree of thermal spread of the ion distribution.
Statement of the problem

A transverse relativistic shock is defined by the condition that the angle between the direction of the magnetic field upstream of the shock and the shock normal be much smaller than $1/\gamma$, where $\gamma$ is the Lorentz factor of the fluid upstream of the shock. This actually makes most relativistic shocks transverse.

The problem with transverse shocks is that particle acceleration cannot be explained as a result of the Fermi I process. An alternative mechanism is shock drift acceleration. Yet in the clearest example of such a shock configuration in nature, i.e. the reverse shock terminating the pulsar wind in plerions, the latter is probably ruled out as well (Hoshino et al., 1992). Yet, particle acceleration is universally believed to be produced at those shocks...

A possible alternative mechanism is the Resonant Cyclotron Absorption process (RCA)
Basic idea behind RCA

Assumptions

- The upstream plasma is made mostly of pairs but contains a small fraction $n_i$ of ions carrying most of the energy.
- The plasma is neutral, cold in its rest frame and $E \times B$ drifting towards the shock at a relativistic velocity.

Plasma behaviour at the shock

- Magnetic field enhancement causes particles of species $s$ to start gyrating at a frequency $\Omega_i$.
- Particle distribution in transverse momentum space is very close to a *cold ring*.
- Gyration is accompanied by emission of cyclotron waves with a spectrum extending from $\Omega_i$ to infinity.
- Pairs thermalize within a few tens of their gyration periods (gyration radii from the shock).
- Waves emitted by the ions at high harmonic multiples $n$ of their gyration frequency can be resonantly absorbed by the pairs.
- Resonant absorption starts at $n = m_i/m_\pm$ and then becomes possible at lower and lower values of $n$. 
Numerical investigations

PIC (Particle In Cell) code: self-consistently solving particle equations of motion and Maxwell's equations

Previous investigations (Hoshino et al., 1992), adopting mass ratios between the ions and the pairs up to a value of 20, showed that RCA could produce efficient acceleration of positrons.

Extrapolation of the results to realistic mass ratios based on linear theory of cold ring instability taking place in a spatially uniform plasma of analogous composition (Hoshino & Arons, 1991). This shows:

- Mild dependence of the growth rates on harmonic number
- Polarization of the waves closer to linear as the pair plasma becomes closer to neutral

Expectation: a larger mass ratio, allowing to have the same amount of energy with a smaller fraction of ions, should not only let the acceleration be still possible but also produce acceleration of electrons.

Present investigation: mass ratios up to 100 are used, acceleration of electrons is observed for the first time, role of ion thermal dispersion is pointed out.
Numerical simulations of relativistic transverse shocks in $e^+-e^−-p$ plasma

We performed 1D numerical simulations with XOOPIC (Verboncoeur at al., 1995)

Plasma is continuously injected in the simulation box from the left boundary while the right boundary is a conducting wall

The figures below show the typical distribution of particle velocities and fields observed in the simulations when the reverse shock has propagated far enough from the right wall

**Particle distribution in $(x,u_x)$ space**

**The electromagnetic field components**

These figures refer to a simulation with $m_i/m_±=100$ and $n_i/n_±=0.1$. The plasma upstream is cold and with a drift Lorentz factor $\gamma=40$ ($\gamma^2=1+u_x^2+u_y^2$). The magnetic field strength in all plots corresponds to $\sigma_±=2$.

The x-coordinate is scaled in units of the pair Larmor radius upstream ($r_L$).

The shock front is at $x/r_L\sim600$, as is evident from the field structure. The first ion reflection loop is also very clear. Close to the shock, ion distribution in $(u_x,u_y)$ space is very close to a cold ring, while the pair plasma thermalizes within a few $r_L$. 
Study of the linear stage of ion cold ring instability in a thermal background pair plasma in the spatially uniform case

In this figure we plot the linear growth rate for the different harmonic of the ion cyclotron series. In each panel the upper curves represent the real part of the dispersion relation while the lower ones are the growth rates. The dispersion relation is solved for a perfectly cold ring with different fractions of ions in the two upper panels, and for the same plasma as in the top left panel but including a different initial spread in velocities in the two lower panels.

For each species \( \sigma_s \) is defined as:

\[
\sigma_s = \frac{B^2}{4 \pi n_s m_s y c^2}
\]

For a truly cold ring the linear growth rates depend very little both on the harmonic number \( n \), and on the exact fraction of energy that is in the ions as long as this is large. The growth at high values of \( n \) is however effectively inhibited by the presence of a thermal spread in the initial velocity distribution of the ions. The polarization of the waves always depends on the number fraction of ions, tending to linear as \( n_i \) decreases.
Dependence of the acceleration on the polarization of the waves

\[ \frac{m_i}{m_e} = 20 \quad \frac{n_i}{n_e} = 0.4 \]

\[ \frac{m_i}{m_e} = 40 \quad \frac{n_i}{n_e} = 0.2 \]

In the figures above we show the distribution function of the particles at different distances behind the shock (the shock front is at \( x/r_L \sim 100 \) in the left panel and at \( x/r_L \sim 200 \) in the right panel). In the left panel the results of Hoshino et al (1992) are reproduced. In the panel on the right a plasma with the same values of \( \sigma_i \) and \( \sigma_\perp \) but with a different number fraction of ions is used. The dashed and solid black curves in each panel represents a fit to the final particle distribution attended using a relativistic maxwellian and a maxwellian plus power law tail, respectively, i.e. the function \( N(\gamma) \) below, with \( N_t = 0 \) and \( f = 1 \) in the first case:

\[ N(\gamma) = f \frac{N_i \gamma}{T'(T' + 1)} \exp\left(-\frac{\gamma - 1}{T'}\right) + N_t \left(\frac{\gamma}{\gamma_m}\right)^{-\alpha} \left[1 - \exp\left(-\frac{\gamma - 1}{\gamma_m}\right)\right] \]

In the left panel the distribution of electrons is consistent with a relativistic maxwellian with no suprathermal tail while the positrons show a well developed power-law tail. In the right panel the efficiency of positron acceleration has decreased, but signs of electron acceleration are seen.
Simulations with \( m_i / m_± = 100 \)

\( n_i / n_± = 0.1 \)

\( n_i / n_± = 0.2 \)

In the figures we show the particle distribution functions at different distances from the shock front which is at \( x/r_L \sim 500 \). Progressive acceleration of a suprathermal tail of both electrons and positrons is observed in both cases, but with different efficiencies.

We report in the table the best fit values of the parameters defining \( N(\gamma) \) as described above. In the last row we report the acceleration efficiency defined as the fraction of particles that are found in the suprathermal tail.

<table>
<thead>
<tr>
<th></th>
<th>( n_i/n_e = 0.1 )</th>
<th>( n_i/n_e = 0.2 )</th>
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<tr>
<td></td>
<td>Electrons</td>
<td>Positrons</td>
</tr>
<tr>
<td>( f )</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>( T' )</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>( \gamma_m )</td>
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<tr>
<td>( N_t )</td>
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</tr>
<tr>
<td>( \alpha )</td>
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<td>-2.9</td>
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<tr>
<td>( r )</td>
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<td>3</td>
</tr>
<tr>
<td>eff[%]</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

We notice that the power-law of suprathermal positrons is always flatter than for electrons, although the differences become smaller with decreasing ion fraction. The global energy transfer scales roughly proportionally to the fraction of energy that is carried by the ions.
Dependence of the acceleration process on the initial velocity dispersion of the plasma

The plots shown below refer to the post-shock evolution of a simulation plasma that is completely analogous to that considered in the previous slide, except for the fact that we have now introduced an initial velocity dispersion: $\delta u/u=0.1$.

From comparison of both the figures and the values in the table with those on the previous slide is clearly seen that the acceleration efficiency is greatly reduced.
Conclusions

We have studied the process of particle acceleration at relativistic transverse shocks within the framework of the RCA model. We have performed numerical simulations with mass ratios between the ions and the pairs up to a factor of 5 higher than before. This fact has allowed us to have a smaller fraction of ions carrying a large fraction of the energy in the plasma. Such a situation causes the polarization of the ion cyclotron waves to be closer to linear and acceleration of electrons to become possible. In fact we do observe a suprathermal population of electrons, although we still see preferential positron acceleration, due to the fact that the fraction of ions we include is still relatively large. Our simulations show that going towards larger and more realistic values of the mass ratio between the ions and the pairs does not inhibit the acceleration, but we point out another factor that could potentially kill the acceleration process, i.e. the initial spread of the ion velocity distribution.

References